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Evaluating the suitability of acoustical measurement techniques and psychophysical testing for studying the consistency of musical wind instrument manufacturing

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Abstract: Musicians often claim to be able to discern differences in the playing properties of musical wind instruments that have been manufactured in exactly the same way. These differences are most likely due to disparities in bore profile or in the positioning and sealing of any valves or side holes. In this paper, the suitability of acoustic pulse reflectometry and a capillary-based impedance measurement technique for detecting differences between instruments of the same model is explored through measurements on two low-cost, mass-produced trumpets. Differences in the measured bore profiles of the two instruments are reported, with the largest deviation caused by the presence of a leak in the third valve of one of the trumpets. Differences in input impedance measurements made on the two instruments are also noted, with the main cause shown to be the leaky valve. Controlled playing tests are carried out using the same two trumpets in order to evaluate the effectiveness of psychophysical testing in establishing whether there are perceptible differences in the playing properties of nominally identical wind instruments. A semi-professional musician is proved to be able to discriminate between the trumpets whereas an amateur player is shown to be unable to do the same.

Keywords: musical wind instruments, input impedance, acoustic pulse reflectometry, psychophysical testing, manufacturing consistency

PACS: 43.58.Bh, 43.75.Fg, 43.75.Yy, 43.66.Yw

1. Introduction

For large-scale musical wind instrument manufacturers, the ability to produce instruments in a repeatable fashion is essential. However, despite the tight manufacturing tolerances used, musicians often claim to be able to discern small, but perceptible, differences between the playing properties of instruments manufactured in exactly the same way. These differences are most likely a result of tiny disparities in bore profile or in the positioning and sealing of any valves or side holes. Physical variations such as these will result in the instruments having non-identical resonance characteristics.

In recent years, development work on non-invasive techniques for measuring the bore profile and the input impedance of musical wind instruments has resulted in significant improvements in both their accuracy and speed [1-3]. Acoustic pulse reflectometry is now capable of measuring the internal radius at regular intervals along an instrument's bore to within an accuracy of ± 0.02 mm [4]. Indeed, its accuracy is such that instrument makers are beginning to use the technique as part of their quality control process. Meanwhile, capillary-based impedance measurement apparatus is now capable of determining the frequencies and amplitudes of an instrument's resonances within a few seconds and with a high degree of repeatability [5]. Both techniques are now sufficiently accurate to make them extremely useful in looking for small physical and acoustical differences between instruments. It is

worth noting that the input impedance of an instrument can be directly deduced from its bore profile and vice-versa so, in principle, it is only necessary to use one of the techniques when measuring an instrument. However, acoustic pulse reflectometry is primarily designed for determining bore information while capillary-based systems are optimised for measuring input impedance. Therefore, the two techniques are often used in combination.

Even the tiniest physical and acoustical variations over a set of instruments can result in musicians claiming that the instruments have noticeably different playing properties. To establish systematically whether musicians can perceive differences between nominally identical instruments, it is necessary to carry out controlled playing tests. Psychophysical testing is regularly used in the commercial sector to investigate whether consumers are able to discriminate between similar, but non-identical, products. Several methods have been developed for this purpose [6]. For example, the 2-alternative forced-choice test with warm-up has shown its efficiency as a test for discriminating between fizzy drinks containing various quantities of caffeine [7]. Methods of this type can be readily adapted to musical instrument playing tests.

The aims of this paper are (i) to demonstrate the suitability of acoustic pulse reflectometry and capillary-based impedance measurement apparatus for detecting physical and acoustical differences between instruments of the same model type produced by the same maker, and (ii) to demonstrate the effectiveness of psychophysical testing in establishing whether there are perceptible differences in the playing properties of such instruments. To this end, experimental measurements and controlled playing tests have been carried out using two low-cost, mass-produced Pearl River MK003 trumpets (see Figure 1).

The current investigation is part of a wider study concerned with evaluating and improving the consistency of musical instrument manufacturing.



Figure 1 Two Pearl River MK003 trumpets

2. Acoustic pulse reflectometry measurements

Acoustic pulse reflectometry has become established as an efficient non-invasive method of measuring the internal dimensions of tubular objects. The technique is particularly useful in the study of musical wind instruments [8] as it is able to provide geometrical information at locations that are inaccessible to direct measurement. In this section, the technique is used to measure the bore profiles of the two Pearl River trumpets under investigation.

a. Reflectometry technique



Figure 2 Acoustic pulse reflectometer coupled to trumpet

Acoustic pulse reflectometry involves injecting a pulse of sound into a tubular object and digitally recording the resultant reflections. Suitable analysis of these reflections provides the input impulse response and then the internal dimensions of the object.

Figure 2 shows the reflectometer used to measure the trumpets in the present study. A 1 V electrical pulse of width 80 μ s is produced by the D/A converter of a National Instruments NI USB-6259 board controlled by a PC. The pulse is amplified by a Cambridge A1 audio amplifier and used to drive a Fane CD150 compression driver loudspeaker. The resultant sound pressure pulse travels along a 12.2 m long source tube of internal diameter 10.0 mm into the trumpet under test. A Knowles EK3132 electret microphone, embedded part of the way along the source tube, records the reflections returning from the trumpet. The microphone signal is amplified, sampled by an A/D converter on the data acquisition board (using a sampling frequency of 50 kHz and a sample length of 2048 points) and stored on the PC. This procedure is repeated 100 times and the samples are averaged to improve the signal-to-noise ratio.

The purpose of the source tube is to ensure that the input pulse, trumpet reflections and secondary loudspeaker reflections are temporally separated. The input impulse response of the trumpet can then be determined by deconvolving the sampled reflections with the input pulse shape. Following a calibration to correct the dc component of the input impulse response [9], the application of a bore reconstruction algorithm [10] enables the internal dimensions of the trumpet to be evaluated.

b. Results

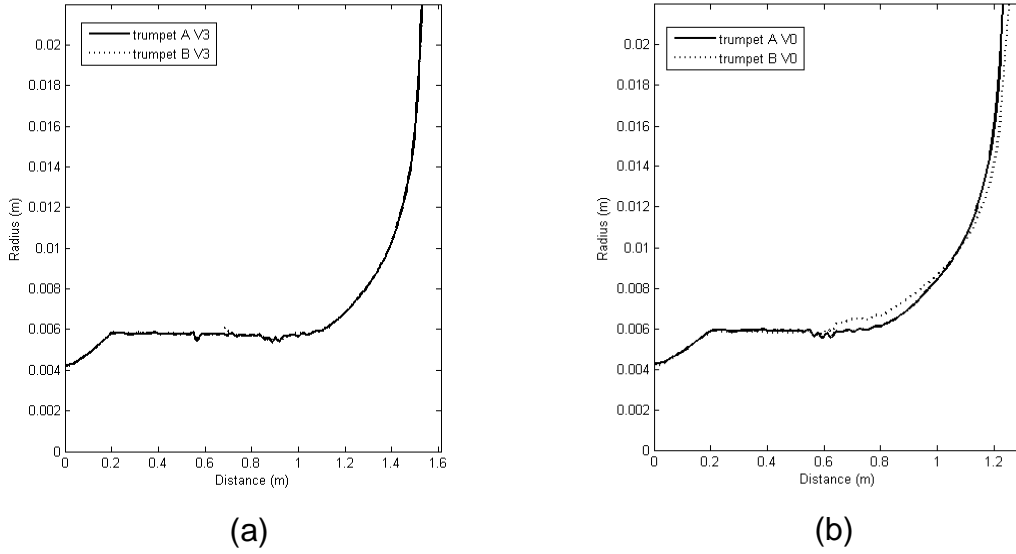


Figure 3 Bore reconstructions of two Pearl River MK003 trumpets with (a) the third valve pressed down (i.e. V3) and (b) no valves pressed down (i.e. V0)

Bore profile measurements have been made for the two trumpets in every possible valve configuration. The results fall into two distinct groups. For those fingerings that involve the third valve being pressed down (i.e. V3, V1+V3, V2+V3, V1+V2+V3), the bore reconstructions of the two instruments are in close agreement. However, for those fingerings where the third valve is not pressed down (i.e. V0, V1, V2, V1+V2), the bore reconstructions diverge from the position of the third valve onwards.

Examples of these two groups of results can be seen in Figure 3 which shows bore profile measurements for the two trumpets with (a) just the third valve pressed down and (b) no valves pressed down. In Figure 3(a), the bore reconstructions of the two trumpets are virtually identical. In Figure 3(b), however, the bore reconstruction for trumpet B begins to expand spuriously at an axial distance of approximately 0.58 m, which corresponds to the position of the third valve. This expansion clearly doesn't represent a physical change in the geometry of the instrument bore, as the act of pressing or depressing a valve does not affect the shape of the instrument bell. In fact, an unexpected expansion of this type in an acoustic pulse reflectometry bore profile measurement often indicates the presence of a leak in the wall of the instrument. As reported in [11], a leak presents a reduction in the impedance seen by the incoming pulse that is similar to the change in impedance caused by a widening of the instrument bore. Hence, the leak appears as a spurious expansion in the bore reconstruction. The consequence is that, if an instrument contains one or more leaks, only the section of the bore before the position of the first leak is reconstructed accurately. In [11], this feature is exploited to provide a method of detecting leaks in tubular objects.

Visual inspection of the third valve of trumpet B reveals a tiny hole in the wall of the lower channel (see Figure 4). This channel forms part of the bore of the instrument when the valve is left in the open position. When the valve is pressed down, however, the lower channel is replaced in the instrument bore by the middle channel, the upper channel and a section of external tubing. This explains why the presence of the leak is only observed in bore reconstructions for fingerings where the valve is open. The hole is so small (with dimensions of approximately $650\text{ }\mu\text{m} \times 250\text{ }\mu\text{m}$) that it is hard to spot with the naked eye and would be difficult to detect without the help of the reflectometry technique.



Figure 4 Third valve of trumpet B with leak in wall of lower channel.

To confirm that the hole in the lower channel of the third valve was the cause of the spurious expansion observed in the bore profile measurements on trumpet B, further experiments have been carried out with the hole sealed using a small quantity of putty. Figure 5 compares the previously measured bore profile of trumpet A with no valves depressed with the new bore profile measurement for trumpet B. In contrast to Figure 3(b), the two curves are now in close agreement confirming that the hole was responsible for the previously observed differences in the measured bore profiles.

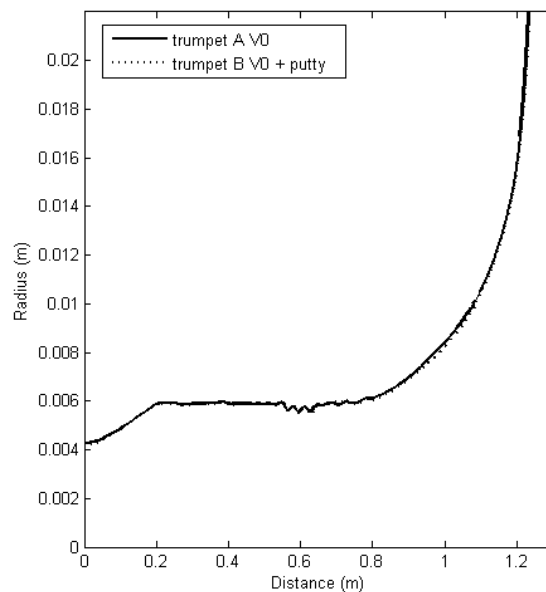


Figure 5 Bore reconstructions of two Pearl River MK003 trumpets with no valves pressed down and the hole in the third valve of trumpet B sealed

It is evident that the bore reconstructions of the two trumpets deviate significantly from each other as a result of the leak in the third valve of trumpet B. However, close inspection of Figure 3(a) and Figure 5 reveals that there are still minute differences in the measured bore profiles even when the leak is not present in the instrument bore (either because the third valve is pressed down or because the leak has been sealed).

3. Input impedance measurements

The input impedance of a musical wind instrument is the ratio of the acoustic pressure to the volume velocity at the entrance to the instrument. By measuring the input impedance, detailed information regarding the frequencies, amplitudes and quality factors of the instrument's air column resonances can be found.

To investigate whether the physical differences between the two Pearl River MK003 trumpets (most noticeably the leak discovered in the third valve of trumpet B) result in significant differences in the resonance characteristics of the instruments, a series of input impedance measurements has been carried out.

a. Capillary-based impedance measurement technique

One of the most established techniques for measuring the input impedance of a wind instrument involves exciting the instrument under investigation at its input with a sinusoidal pressure wave supplied via a high impedance capillary [3, 12, 13]. The capillary ensures that the excitation wave has a volume flow rate that is approximately independent of the air column being measured. The frequency of the excitation wave is increased and the pressure response at each frequency is recorded by a microphone positioned at the instrument input. The input impedance is then found by performing a complex division of the pressure response by the volume flow rate. (The magnitude and phase of the volume flow rate are determined by performing a calibration measurement using an object whose impedance is well known theoretically).

In the present study, a commercially available capillary-based impedance measurement system has been used to measure the two trumpets. The BIAS system [5] was developed specifically for the study of brass instruments. Although based on the above principles, it uses a single chirp excitation signal rather than a number of sinusoidal signals of increasing frequency. As a result, it provides both quick and repeatable measurements of input impedance.

b. Results

Using the BIAS system, input impedance measurements have been made with the two trumpets in every possible valve configuration. The same mouthpiece was used for both trumpets and three measurements were made for each fingering to ensure that repeatable results were achieved (for all fingerings, the observed difference in the peak amplitudes for the three measurements was no greater than 2 MOhm while the observed difference in the peak frequencies was no greater than 0.5 Hz).

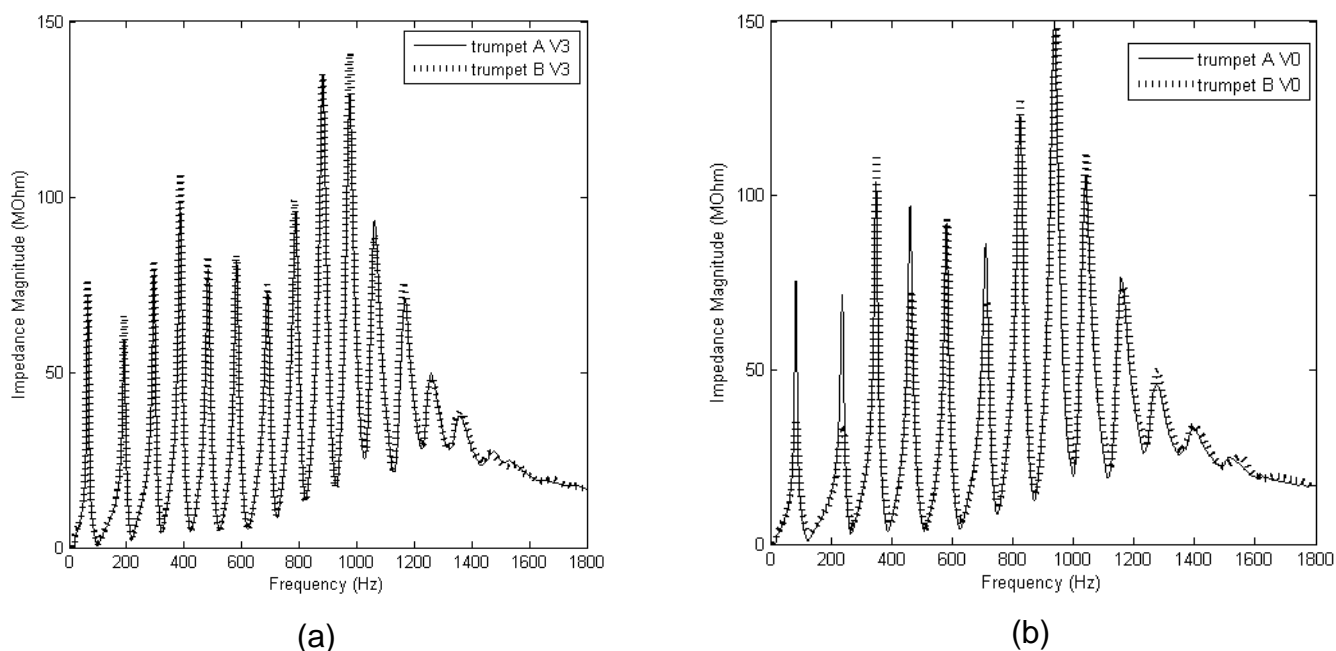


Figure 6 Input impedance magnitude curves for two Pearl River MK003 trumpets with (a) the third valve pressed down (i.e. V3) and (b) no valves pressed down (i.e. V0)

As with the bore profile measurements, the results fall in two distinct groups. For those fingerings that involve the third valve being pressed down, the input impedance measurements for the two instruments are in close agreement. However, for those fingerings where the third valve is not pressed down, the impedance measurements show large differences.

Figure 6 shows input impedance magnitude curves for the two trumpets with (a) just the third valve pressed down and (b) no valves pressed down. In Figure 6(a) the two impedance curves are very similar. However, in Figure 6(b), much larger differences can be observed between the two curves. This is particularly true for the first two peaks, which have significantly lower amplitudes in the case of trumpet B.

A quantitative analysis of these curves is given in Tables 1 and 2. Table 1 presents the frequencies, equivalent pitches, amplitudes and quality factors (where the quality factor is defined as the frequency of the peak divided by the half-power bandwidth) of the first nine peaks for the two impedance curves of Figure 6(a). The difference in frequency between corresponding resonance peaks is no greater than 1 Hz for eight of the nine peaks. For the remaining peak, the difference is still only 3.6 Hz. More pertinently, the equivalent pitch difference between corresponding peaks is less than or equal to 7 cents ($7/100^{\text{th}}$ of a musical semitone) in all cases. Meanwhile, the difference in amplitude between corresponding peaks never exceeds 10% (and is less than 4% for seven of the nine peaks) while the difference in quality factor never exceeds 8%. The observed differences are clearly very small. However, it is worth noting that for all nine resonances, the peak frequencies for trumpet B are less than or equal to those for trumpet A while the peak amplitudes and the quality factors for trumpet B are greater than those for trumpet A. This suggests that for notes played using the V3 fingering, trumpet B might be expected to play slightly flatter than trumpet A. For this fingering, trumpet B might also be expected to produce the notes slightly more easily than trumpet A. However, the differences between the impedance curves are so small that it is questionable whether these effects will actually be perceptible.

Table 2 presents similar information for the impedance curves of Figure 6(b). Now the difference in frequency between corresponding peaks is greater than 1 Hz for eight of the nine peaks. In fact, for three peaks the difference is greater than 5 Hz. This leads on to the

difference in equivalent pitch between corresponding peaks being greater than 10 cents ($1/10^{\text{th}}$ of a musical semitone) in the majority of cases. Meanwhile, the difference in amplitude and quality factor between corresponding peaks is greater than 10% for four of the nine peaks. Indeed, for the first two peaks the difference in amplitude and quality factor is actually greater than 85%. These differences are clearly much larger than those seen in Figure 6(a). Moreover, the peak frequencies for trumpet B are now all higher than those for trumpet A. This suggests that, for notes played using the V0 fingering, trumpet B might be expected to play sharper than trumpet A. In addition, for the four peaks where the differences are most significant, the peak amplitudes and quality factors for trumpet B are all lower than those for trumpet A. Therefore, for several notes played using this fingering, trumpet A might be expected to produce the notes more easily than trumpet B but with a less bright timbre. As the differences between the impedance curves are reasonably large, it is quite possible that these effects will be perceptible to a player.

It is evident from the discussion that the most significant differences between the impedance curves for the two trumpets occur for those fingerings where the third valve is in the open position. In a similar manner to Section 2, in order to verify that the small hole in the third valve of trumpet B was the cause of the large differences observed between the impedance curves, further experiments have been carried out with the hole sealed using putty. Figure 7 compares the previously measured impedance curve for trumpet A with no valves depressed with the new input impedance magnitude measurement for trumpet B. In contrast to Figure 6(b), the two curves are now in much closer agreement.

A quantitative analysis of the impedance curves displayed in Figure 7 is provided in Table 3. The difference in frequency between corresponding resonance peaks is less than 3 Hz for seven of the nine peaks. For the remaining two peaks, the difference is still only 5.2 Hz. In terms of equivalent pitch, the difference is less than or equal to 11 cents ($11/100^{\text{th}}$ of a musical semitone) in all cases. More significantly, the amplitude difference between corresponding peaks never exceeds 3% while the greatest observed difference in quality factor is 5.1%. It is clear that now that the hole has been sealed, the differences between the impedance curves are much smaller. However, it is worth noting that, even with the leak sealed, the peak frequencies for trumpet B are still all higher than those for trumpet A for the V0 fingering. So, for notes played with this fingering, trumpet B might still be expected to play slightly sharper than trumpet A. There is no clear trend with regard to the peak amplitudes and quality factors over the nine resonances analysed. It is therefore hard to say whether a given note will be harder to sound, or whether it will have a different timbre, on one instrument or the other. Regardless, the differences between the impedance curves are so small that these effects may well be imperceptible.

It is clear that the leak in the third valve of trumpet B causes large differences between the impedance curves for the two trumpets. However, close inspection of Figure 6(a) and Figure 7, together with the discussion provided in this section, reveals that small differences still exist between impedance curves for the two trumpets when the leak is no longer a factor (either because valve 3 has been pressed down or because the leak has been sealed). This is not too surprising given the observation made in Section 2 that the bore reconstructions of the two trumpets still exhibit small differences even after the leak has been removed from the instrument bore.

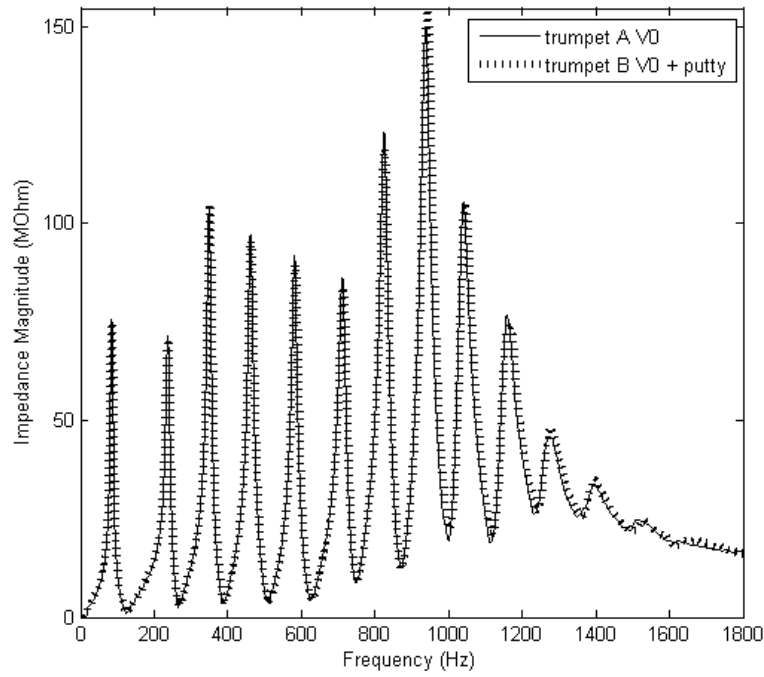


Figure 7 Input impedance magnitude curves for two Pearl River MK003 trumpets with no valves pressed down and the hole in the third valve of trumpet B sealed

Table 1. Frequencies (F), equivalent pitches (EP), amplitudes (A) and quality factors (Q) of impedance magnitude peaks for two Pearl River MK003 trumpets with third valve pressed down (extracted from data plotted in Figure 6(a))

V3	Peak number	1	2	3	4	5	6	7	8	9
Tpt A	F_A (Hz)	65	191.5	295	386.3	483.3	582.5	689.5	788.3	882
	EP_A	C2-12c	G3-41c	D4+8c	G4-25c	B4-38c	D5-14c	F5-22c	G5+9c	A5+4c
	A_A (MOhm)	75.2	59.9	79.9	96.6	80	80.4	73.3	95.7	134.7
	Q_A	9.0	19.3	27.8	31.7	32.0	39.6	39.2	40.0	40.2
Tpt B	F_B (Hz)	64.8	190.7	294.5	386	482.3	581.5	689.5	784.7	881
	EP_B	C2-17c	G3-47c	D4+5c	G4-27c	B4-41c	D5-17c	F5-22c	G5+2c	A5+2c
	A_B (MOhm)	76.5	66.4	81.8	106.7	83	83.3	74.9	99.1	135.2
	Q_B	9.4	20.5	28.0	33.3	34.7	40.4	41.0	41.3	42.0
Diff	$F_B - F_A$ (Hz)	-0.2	-0.8	-0.5	-0.3	-1	-1	0	-3.6	-1
	$EP_B - EP_A$	-5c	-6c	-3c	-2c	-3c	-3c	0c	-7c	-2c
	$100 * (A_B - A_A) / A_B$ (%)	1.7	9.8	2.3	9.5	3.6	3.5	2.1	3.4	0.4
	$100 * (Q_B - Q_A) / Q_B$ (%)	4.3	5.9	0.7	4.8	7.8	2.0	4.4	3.1	4.3

Table 2. Frequencies (F), equivalent pitches (EP), amplitudes (A) and quality factors (Q) of impedance magnitude peaks for two Pearl River MK003 trumpets with no valves pressed down (extracted from data plotted in Figure 6(b))

$V0$	Peak number	1	2	3	4	5	6	7	8	9
$Tpt A$	F_A (Hz)	84	237	348.9	461.6	581	710.8	824.7	937.3	1040.4
	EP_A	E2+41c	Bb3+29c	F4-2c	Bb4-17c	D5-19c	F5+30c	G#5-12c	Bb5+9c	C6-10c
	A_A (MOhm)	75.5	71.6	103.7	96.9	91.8	86.3	122.3	149.9	105.5
	Q_A	10.4	21.7	30.1	33.0	41.2	38.6	40.4	38.4	35.8
$Tpt B$	F_B (Hz)	85	238.5	350.9	469.9	583	716.4	825	943.6	1042.4
	EP_B	F2-47c	Bb3+40c	F4+8c	Bb4-1c	D5-13c	F5+44c	G#5-12c	Bb5+21c	C6-7c
	A_B (MOhm)	34.8	33.1	110.8	72.7	93.7	68.8	126.9	148.5	112.4
	Q_B	5.6	8.9	30.3	25.7	39.7	30.6	38.0	37.0	37.8
$Diff$	$F_B - F_A$ (Hz)	1	1.5	2	8.3	2	5.6	0.3	6.3	2
	$EP_B - EP_A$	12c	11c	10c	16c	6c	14c	0c	12c	3c
	$100 * (A_B - A_A) / A_B$ (%)	-117.0	-116.3	6.4	-33.3	2.0	-25.4	3.6	-0.9	6.1
	$100 * (Q_B - Q_A) / Q_B$ (%)	-85.7	-143.8	0.7	-28.4	-3.8	-26.1	-6.3	-3.8	5.3

Table 3. Frequencies (F), equivalent pitches (EP), amplitudes (A) and quality factors (Q) of impedance magnitude peaks for two Pearl River MK003 trumpets with no valves pressed down and the hole in the third valve of trumpet B sealed (extracted from data plotted in Figure 7)

$V0+putty$	Peak number	1	2	3	4	5	6	7	8	9
$Tpt A$	F_A (Hz)	84	237	348.9	461.6	581	710.8	824.7	937.3	1040.4
	EP_A	E2+41c	Bb3+29c	F4-2c	Bb4-17c	D5-19c	F5+30c	G#5-12c	Bb5+9c	C6-10c
	A_A (MOhm)	75.5	71.6	103.7	96.9	91.8	86.3	122.3	149.9	105.5
	Q_A	10.4	21.7	30.1	33.0	41.2	38.6	40.4	38.4	35.8
$Tpt B$	F_B (Hz)	84.5	237.5	351	463.2	583.8	713.7	825.5	942.5	1045.6
	EP_B	E2+44c	Bb3+33c	F4+9c	Bb4-11c	D5-10c	F5+37c	G#5-11c	Bb5+19c	C6-1c
	A_B (MOhm)	75.0	70.7	104.9	95.8	89.6	83.9	119	154.6	104.8
	Q_B	10.4	21.0	30.3	32.6	39.2	37.2	41.1	38.6	35.9
$Diff$	$F_B - F_A$ (Hz)	0.5	0.5	2.1	1.6	2.8	2.9	0.8	5.2	5.2
	$EP_B - EP_A$	3c	4c	11c	6c	9c	7c	1c	10c	9c
	$100 * (A_B - A_A) / A_B$ (%)	-0.7	-1.3	1.1	-1.1	-2.5	-2.9	-2.8	3.0	-0.7
	$100 * (Q_B - Q_A) / Q_B$ (%)	0	-3.3	0.7	-1.2	-5.1	-3.8	1.7	0.5	0.3

4. Psychophysical testing

In order to establish whether the physical and acoustical differences between the two Pearl River MK003 trumpets result in perceptible differences in their playing properties, psychophysical tests have been carried out by one semi-professional musician and by one amateur musician.

a. 2-alternative forced-choice test with warm-up

The type of playing test deemed appropriate to the problem of discriminating the two trumpets is the 2-alternative forced-choice test with warm-up. At the start of the test, the musician is given a few minutes to play the two instruments (referred to throughout the tests simply as trumpet A and trumpet B) and become familiar with them. Following this, two warm-up trials take place in which the trumpets are presented in a random order. By playing them both, the musician attempts to determine which instrument is which. After each warm-

up trial, the musician is informed whether they answered correctly or not. Finally, the pair of trumpets is presented twenty further times in a random order and each time the musician is again asked to judge which instrument is which. At all stages in the test, the musician is free to play whatever notes and/or melodies that they choose.

Before the test, the musician is informed that the purpose is to evaluate if there are perceptible differences between the two mass-produced trumpets. At the end of the test, the musician is asked to describe in words the differences they felt.

b. Results

Each musician was asked to carry out two separate playing tests in succession. During the first test, the hole in the third valve of trumpet B was left open. In the second test, the leak was sealed using putty.

In both playing tests, the semi-professional musician gave 16 correct answers out of a possible 20. Using a binomial probability distribution, the probability of achieving 16 or more correct answers by chance is only 0.59%. It can therefore be concluded that, at the 1% significance level, this musician was able to perceive a difference between the instruments. The semi-professional musician was able to discriminate between trumpet A and trumpet B whether the hole in the third valve was sealed or not. However, the musician described the two playing tests very differently. For the first test, he made comments such as “*trumpet A was easier to blow than trumpet B*” and “*trumpet B has a brighter sound*”. It is interesting to note that these comments match the playing properties that were hypothesised from the impedance curves of Figure 6(b) in Section 3. However, it should be borne in mind that the musician was encouraged to play any notes during the tests and was not solely constrained to those notes produced with the third valve open. For the second test (with the hole sealed), the musician commented that the test was “*harder*”. He was not able to describe specific differences but spoke more about a “*global feeling*” and reported that “*maybe trumpet B is a little bit brighter*”. In addition, following the seventh trial of the second test, the musician needed a reminder of which trumpet was which. Thus, even though the trumpet player was able to discriminate the instruments in the two sessions, he found the second session to be much more difficult than the first one.

In contrast to the semi-professional musician, the amateur player only achieved 8 correct answers out of possible 20 in the first playing test. According to the binomial distribution, even if the player had randomly guessed the outcome of each trial, the probability that they would have achieved at least 8 correct answers is 86.84%. This is extremely high. There is no statistical evidence, therefore, to suggest that the amateur musician was able to discriminate between the two instruments, even with the leak in the third valve present. As the musician failed to find any difference between the two trumpets under these conditions, it was deemed unnecessary to carry out the second playing test with the leak sealed.

5. Conclusion

An acoustic pulse reflectometer and a capillary-based impedance measurement system have been demonstrated to be extremely effective in identifying physical and acoustical differences between two low-cost trumpets. Bore reconstructions revealed the presence of a leak in the third valve of one of the trumpets. This flaw also had an impact on the input impedance measurements, with large differences seen between the impedance curves of the two trumpets for those fingerings where the third valve was in the open position.

A leak of this type is a relatively gross defect and consequently would be expected to have a large effect on both bore profile and input impedance measurements. However, even when the leak was removed from the instrument bore (either by sealing with putty or by depressing the third valve), small differences could still be observed between the bore reconstructions and input impedances of the two trumpets.

Psychophysical testing has been demonstrated to be an effective way of ascertaining the capacity of musicians to discriminate between the two trumpets. Via controlled playing tests, the ability of a semi-professional musician to discern differences in the playing properties of the two trumpets was established. This ability proved to be the same whether or not the leak was present, although the musician did comment that it was harder to discriminate between the instruments in the case where the leak was sealed. Interestingly, similar playing tests revealed that an amateur player was unable to tell the two trumpets apart even with the leak present. This raises the question of whether the accuracy with which instruments are made becomes more important for instruments aimed at higher level musicians. That said, even with entry level instruments, any leaks within an instrument will most likely grow over time (as a result of the exposure to humid air that occurs when the instrument is played) and so their influence on the playing properties of the instrument might be expected to increase in the future.

It is difficult to draw too many general conclusions from this study regarding the level of consistency with which musical wind instruments are manufactured. Only a single manufacturer's instruments were investigated and just two instruments of the selected model were measured. In addition, the chosen instruments only represented the lower end of the market. Also, only the perceptions of two musicians were investigated.

To explore the larger question of evaluating the consistency of musical wind instrument manufacturing in general, further work is currently being carried out. In this work, the measurement techniques and psychophysical testing procedures evaluated in this paper are being applied to larger numbers of instruments of a given model type (including beginner, intermediate and professional models), to instruments from different makers, and to a wider variety of instruments from both the woodwind and brass families.

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